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PHASE CHARACTERISTICS, COMPOSITION AND POTENTIAL SLAGGING TEMPERATURE OF FURNACE BOTTOM DEPOSITS FROM A PILOT-SCALE RESEARCH BOILER FIRING WESTERN CANADIAN COALS

T.T. Chen, D.H.H. Quon and S.S.B. Wang
Mineral Processing Laboratory

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by

T.T. Chen*, D.H.H. Quon* and S.S.B. Wang*

ABSTRACT

Phase characteristics, compositions and potential slagging temperatures (PST) of furnace bottom deposits (FBD) from a pilot-scale research boiler fueled with subbituminous to bituminous western Canadian coals were studied. In general, the FBD consist of porous aluminosilicate glass, with minor to trace amounts of quartz, cristobalite, mullite, anorthite, iron oxide and hercynite randomly dispersed in the glass matrix; the FBD with lower potential slagging temperature (PST) exhibit a less porous microstructure. FBD produced from the same parent coal under similar combustion conditions are similar in composition, microstructure and phase characteristics, although the FBD produced with a slightly lower fuel rate and finer coal grind have a lower PST. FBD show a higher PST and Si content, and a lower P, Ca, Mg and S content and base/acid ratio than their parent ash. Several correlations are observed for the coal ashes and FBD (with total base < 20 wt %) produced from the same boiler: (1) a decrease of base content or base/acid ratio in the ashes and FBD is accompanied by an increase in PST, (2) an increase of alumina content or a decrease of SiO_2/Al_2O_3 ratio in the ash (not the FBD) is accompanied by an increase in PST, and (3) an increase of mean reflectance value or a decrease of total volatile content in the coal is accompanied by an increase in the PST for the ash. Ash type and blending of coals do not affect correlations.

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*Research Scientist, Mineral Processing Laboratory, Mineral Sciences Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa.

CARACTÉRISTIQUES DES PHASES, COMPOSITION ET TEMPÉRATURE DE SCORIFICATION POTENTIELLE DES DÉPÔTS DE SOLE PRODUITS PAR UNE CHAUDIÈRE EXPÉRIMENTALE ALIMENTÉE EN CHARBONS DE L'OUEST CANADIEN

par

T.T. Chen*, D.H.H. Quon* et S.S.B. Wang*

RÉSUME

Les auteurs ont étudié les caractéristiques des phases, la composition et la température de scorification potentielle (TSP) de dépôts de sole produits par une chaudière pilote alimentée en charbons subbitumineux et bitumineux de l'Ouest canadien. En général, le dépôt de sole est constitué de verre aluminosilicaté poreux et comporte aussi, en quantités mineures ou en traces, du quartz, de la cristobalite, de la mullite, de l'anorthite, de l'oxyde de fer et de l'hercynite dispersés au hasard dans la matrice vitreuse; le dépôt ayant la TSP la plus basse présente la microstructure la moins poreuse. Les dépôts produits par le même charbon et dans les mêmes conditions de combustion sont semblables des points de vue de la composition, de la microstructure et des caractéristiques des phases, quoique ceux qui ont été produits au moyen d'un fuel-ratio un peu plus faible et un charbon plus fin affichent une TSP inférieure. Les dépôts de sole présentent une TSP et une teneur en Si plus élevées, ainsi qu'une teneur en P, Ca, Mg et S et un ratio base-acide plus faibles que les cendres qui leur ont donné naissance. Plusieurs corrélations peuvent être établies entre les cendres de charbon et les dépôts de sole (avec une basicité totale inférieure à <20 % en poids) issus de la même chaudière: (1) une diminution de l'indice de basicité ou du ratio base-acide dans les cendres et le dépôt de sole s'accompagne d'une augmentation de la TSP, (2) à une augmentation de la teneur en alumine ou à une diminution du ratio SiO_2/Al_2O_3 dans les cendres (non dans le dépôt) correspond une augmentation de la TSP et (3) une augmentation de la valeur de réflectance moyenne ou une diminution de la teneur totale en matières volatiles dans le charbon s'accompagne d'une augmentation de la TSP des cendres. Le type de cendres et la composition du mélange de charbons n'influent pas sur ces corrélations.

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*Chercheur scientifique, Laboratoire du traitement des minéraux, Laboratoires des sciences minérales, CANMET, ministère de l'Énergie, des Mines et des Ressources, Ottawa.

INTRODUCTION

As part of an effort to study the slagging and fouling mechanism of coal ash, the phase characteristics of furnace bottom deposits (FBD) produced from a pulverized coal-fired research boiler burning western Canadian coals were studied. The composition and potential slagging temperature (PST)[1] of the FBD produced from the same coal under different firing conditions were compared, as well as those of the parent ash and the FBD. The composition of the ashes and FBD, and the volatile contents of the coals were correlated to the PST. The results are given in this report; the viscosity measurements of these FBD have been reported in a separate study[2].

PARENT COALS AND FURNACE BOTTOM DEPOSITS

FBD samples were produced by the Canadian Combustion Research Laboratory of CANMET in 1982 from a pilot-scale research boiler during the combustion performance evaluations of western Canadian coals. The detailed boiler operation conditions for these trials and the feasibilities of the coals as boiler fuels have been reported by Banks et al.[3,4] and Wong et al.[5,6]. A brief description of the sources, ash fusibilities and chemical compositions of the FBD is given in Tables 1-4.

In brief, the coals used for these combustion tests vary from high volatile subbituminous to low volatile bituminous. After beneficiation, the ash contents vary from 9 to 17 wt %, and the volatile contents from 20 to 35 wt %. In general, two FBD samples were produced from each coal under two separate combustion trials. The boiler operation conditions for the two trials were similar except that one usually had a slightly lower fuel rate, a finer coal grind, or a lower flue gas rate and lower air temperature than the other. For coal containing a high proportion of inert material, the coal was blended with a more reactive coal in several different ratios and tested under similar boiler operation conditions.

PHASE CHARACTERISTICS OF THE FURNACE BOTTOM DEPOSITS

Polished sections were prepared from FBD for this study; the phases were identified using an optical microscope, a scanning electron microscope equipped with energy dispersive X-ray analyzer, and X-ray powder diffractometry. The results are given in Tables 1-4.

In general, the FBD consist mainly of alumino-silicate glass, with minor to trace amounts of quartz, cristobalite, mullite, anorthite, iron oxide and hercynite randomly dispersed in the glass matrix (Fig. 1). Anorthite occurs as needle-like crystals (Fig. 2), obviously having crystallized from the silicate melt during cooling. Iron oxide occurs mainly as dendrites and as spheroids. Mullite frequently occurs as rims surrounding subangular quartz grains (Fig. 3), possibly a product of the reaction between the silicate melt and the residual quartz or a dissociation product of the original mineral matter; however, some mullite apparently has crystallized during cooling and occurs as needle-like crystals. Cristobalite and hercynite occur as fine irregular grains, possibly crystallizing from the melt. Most quartz occurs as coarser subangular to subrounded grains, implying residual mineral matter.

The composition of the glass matrix is mainly alumina and silica, with minor to trace amounts of Fe, Ca, Mg, Ti, K, Na, P, Ba and Sr. The compositions vary slightly from spot to spot, and no systematic variation in the components can be established from the hotter portion (toward fire face) to the cold portion (towards boiler wall) of the FBD, except that a random increase of alumina is compensated by a decrease of silica, similar to those reported previously[7].

All FBD samples except A601-82 and A622-82 are glassy and porous. The varying degree of porosity, as seen in cross-sections of the FBD glasses, is illustrated in Fig. 4, 5 and 6. The porosity of the glass is caused by the release of the entrapped gas from the alumino-silicate melt at high temperature; in general, the FBD with lower ash fusion temperature (or PST) tend to exhibit a less porous microstructure. FBD A601-82 and A622-82 (produced from same coal but blended with a reference coal in different ratios) are powdery, non-glassy, and show varying degree of expansion and are bonded by a glassy phase. In cross-section (Fig. 7,8), they are very porous. Both contain high alumina (27 wt %) and both have a fusion temperature higher than 1454°C. As a conclusion, the FBD with lower

Al_2O_3 content (eg. 20 wt %) tend to show a more glassy texture (Fig. 4,5) than corresponding FBD's with higher alumina content (eg. 26 wt %) (Fig. 7,8).

FURNACE BOTTOM DEPOSITS FROM THE SAME PARENT COAL

In general, FBD produced from the same parent coal under the two combustion conditions[3,4,5,6], are similar in chemical composition, microstructure and phase characteristics, although a slight difference may be found in the relative quantities of the crystalline phases (Tables 1-4). The element enrichment ratios, i.e. (element in FBD)/(element in ash)[8], are similar between the two FBD. However, the FBD produced with a slightly lower fuel rate, finer coal grind, or lower flue gas rate and lower air temperature consistently have a lower potential slagging temperature (PST = $[H_{oxid} + 4.Ired]/5$)[1] than the other FBD.

FURNACE BOTTOM DEPOSITS AND THEIR COAL ASH

From the observations, the following conclusions can be derived:

1. Based on the element enrichment ratios, the FBD studied consistently show a higher Si (ratio = 1.1-1.2), lower P (0.1-0.7), Ca (0.5-0.9), Mg (0.7-0.8) and S (0-0.1) contents than their parent coal ashes. The enrichment ratios for Fe, Ti, Na and K are similar for the FBD produced from the same coal, but vary considerably from coal to coal of different localities and have values ranging from greater than 1.0 to less than 1.0. Presumably the variation from coal to coal is due to the variation in mineral species in the parent coal.

2. Coal ashes have higher base/acid ratios [$(Fe_2O_3+CaO+MgO+Na_2O+K_2O)/(SiO_2+Al_2O_3+TiO_2)$][1] than their FBD, apparently due to the mineral matter in the coal ash containing more base components than the molten slags.

3. Coal ashes usually have lower PST than the corresponding FBD, probably related to the above two observations.

CORRELATION BETWEEN POTENTIAL SLAGGING TEMPERATURE AND COMPOSITION OF ASH AND FURNACE BOTTOM DEPOSIT, AND PROPERTIES OF COAL

One of the common studies on slagging potential of coal is to examine the relation between ash composition and ash fusion temperature[9,10]. The total base content ($\sum Fe_2O_3$, MgO, CaO, Na_2O, K_2O wt %) and base/acid ratio are commonly used for correlations[9,10]. Based on the ashes and FBD produced from the combustion trials, including the above described samples and those reported previously by the others[7,11,12,13], a regression analysis was conducted to correlate the composition of FBD, ash, and physical properties of coal to the PST. The analysis was conducted to fit the equation: $y = a + bx + cx^2$ where x is the PST, and y is the various chemical or physical parameters. The data for the correlations which were found to be significant are given in Table 5. It should be noted that the ashes and FBD were produced from western Canadian coals with ranks varying from high volatile subbituminous to low volatile bituminous; the ashes and FBD have $(CaO + MgO)/Fe_2O_3$ ratios ranging from approximately 0.5 to 2.5, and have total base contents less than 20 wt %. The alkali contents ($Na_2O + K_2O$) are less than 3 wt %, and the SO_3 contents are less than 4 wt % in the ashes.

Correlations of the composition of the ash, FBD and physical properties of coal to PST show the following:

1. A decrease of total base content, or base/acid ratio, in the ash (c.c. = 0.97)* or FBD (c.c. = 0.87) is usually accompanied by an increase of potential slagging temperature (Fig. 9). Both the coal ashes and the FBD follow the same correlation curve, although the FBD usually have lower total base content and lower base/acid ratio (i.e. higher PST) than their parent ash.

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*c.c. = correlation coefficient.

2. An increase of total (CaO, MgO, Fe_2O_3) content in the ashes (c.c. = 0.93) and FBD (c.c. = 0.80) is generally accompanied by a decrease of PST (Fig. 9). This can be easily deduced from the relationship between the total base content and the PST, as the alkali contents in these ashes and FBD are low (less than 3 wt %).

3. An increase of alumina content in the ash (c.c. = 0.96) is usually accompanied by an increase of PST (Fig. 10). Similarly, a decrease of SiO_2/Al_2O_3 ratio (c.c. = 0.93) is accompanied with an increase in PST. The correlations are expected, as the compositions of the ashes and FBD are mainly of alumina and silica ($Al_2O_3 + SiO_2 \geq 80$ wt %). Based on Al_2O_3-SiO_2- (FeO, CaO) phase diagrams, an increase in alumina in the bulk composition is expected to be accompanied by an increase in the liquidus temperature. However, the correlations for the FBD are poor (c.c. = 0.89 and 0.77, respectively).

4. An increase of mean reflectance value (c.c. = 0.95), or a decrease of total volatile content (c.c. = 0.95), in the coal is usually accompanied by an increase of PST for these subbituminous and bituminous coals (Fig. 10).

In general, the correlation between the coal ashes and the PST are better than those between the FBD and the PST. The FBD usually show a poorly defined trend and have a higher PST than their parent ashes. Both the western type [$(CaO+MgO)/Fe_2O_3 > 1.0$] ash and the eastern type [$(CaO+MgO)/ Fe_2O_3 < 1.0$] ash follow in the same correlation trend, as do the blended and non-blended coals. This indicates that ash type and coal-blending do not affect the correlations. The correlations of PST to the total inerts, or total ash contents of coals, and to the Fe_2O_3 and alkali contents of the ashes and the FBD are poor.

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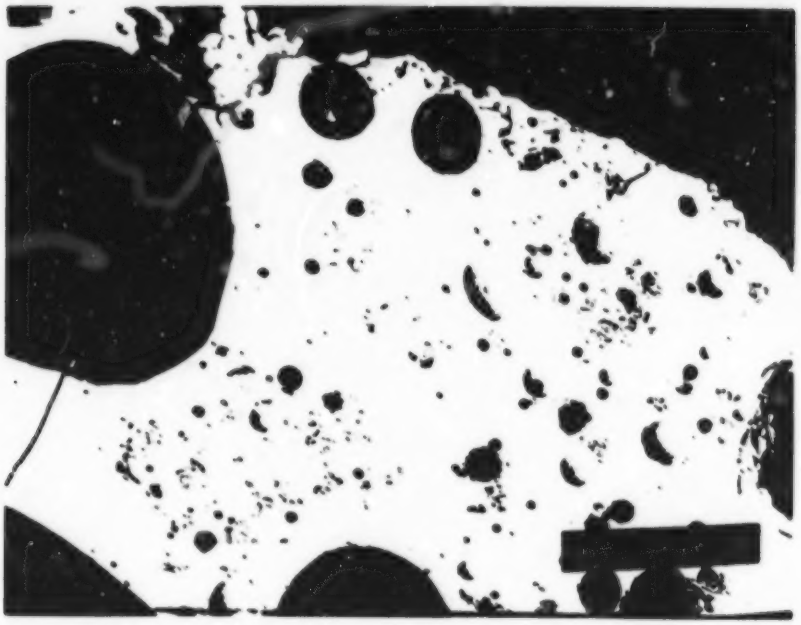

Fig. 1 - General texture of furnace bottom deposit A317-82, showing porous alumino-silicate glass with minor amounts of quartz, cristobalite and mullite randomly dispersed in the glass matrix. BSE image.

Fig. 2 - Furnace bottom deposit A390-82, portion near boiler wall, showing anorthite crystals (needle-like) and Fe oxide dendrites (bright) in matrix of alumino-silicate glass. BSE image.

Fig. 3 - Mullite in the furance bottom deposit (A448-82) usually occurs as rims around sub-angular or sub-rounded quartz grains in the alumino-silicate glass matrix. BSE image.

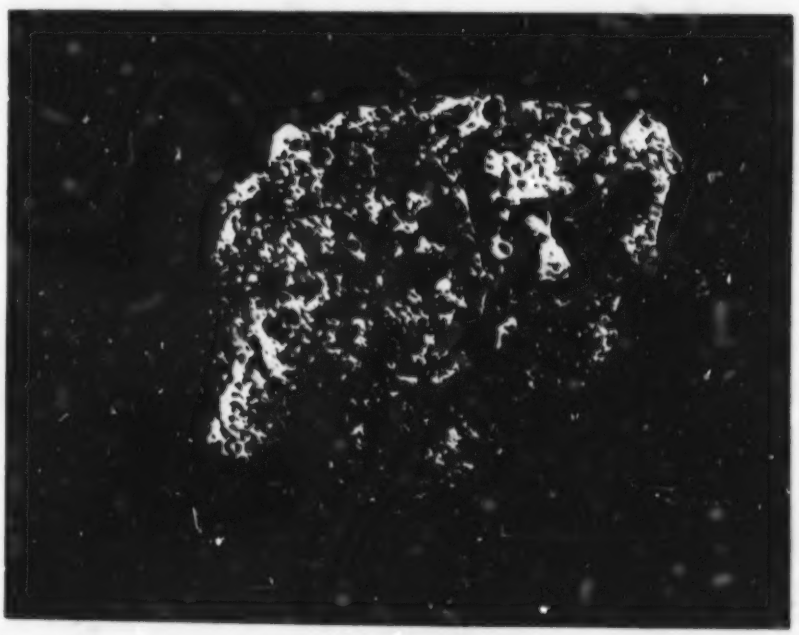

Fig. 4 - Furnace bottom deposit (A448-82) showing a glassy and porous texture.

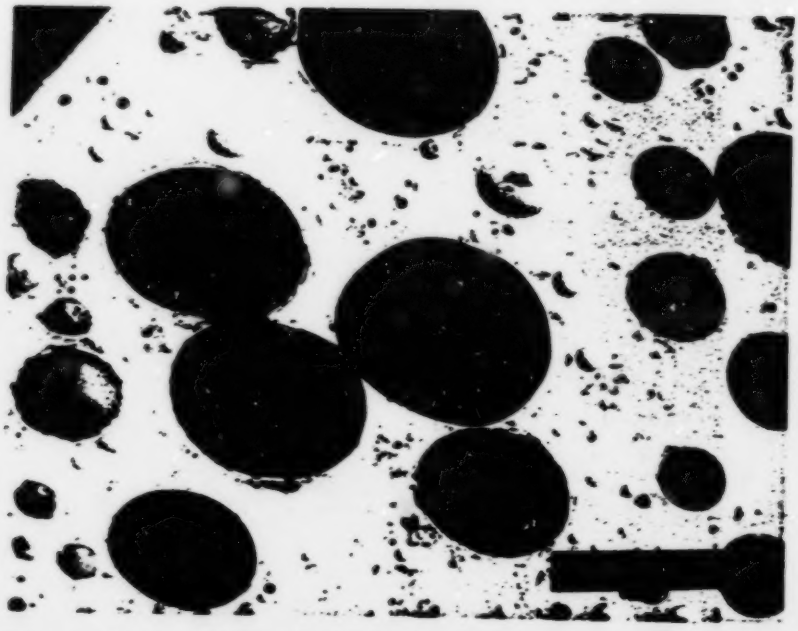

Fig. 5 - Furnace bottom deposit A581-82, showing a vesicular texture on cross-section. The inclusions are mainly quartz, cristobalite and mullite. BSE image.

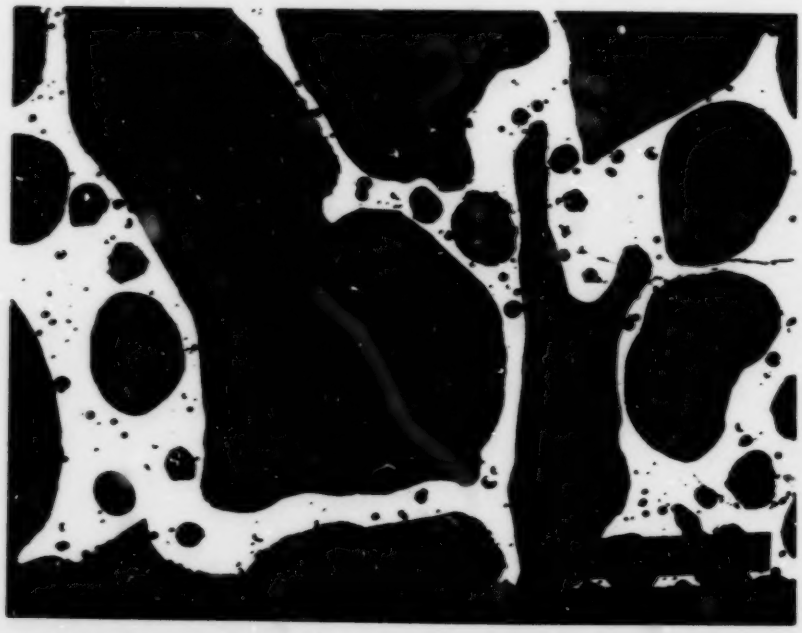

Fig. 6 - Furnace bottom deposit A516-82, showing a very porous (sponge-like) texture on cross-section. BSE image.

Fig. 7 - Furnace bottom deposit A622-82, showing a non-glassy, friable, powdery to sintered-like texture. The material is very light weight.

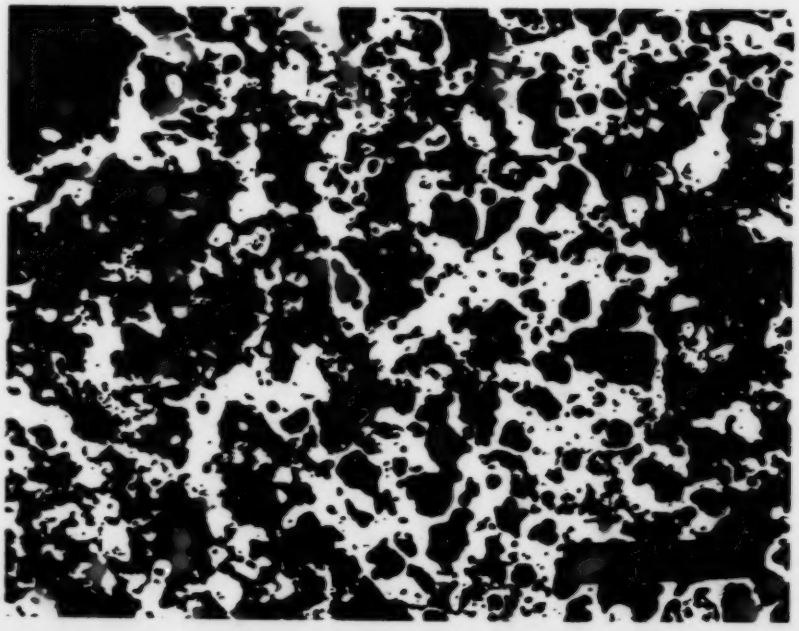

Fig. 8 - Cross-section showing porous texture of furnace bottom deposit A622-82. BSE image.

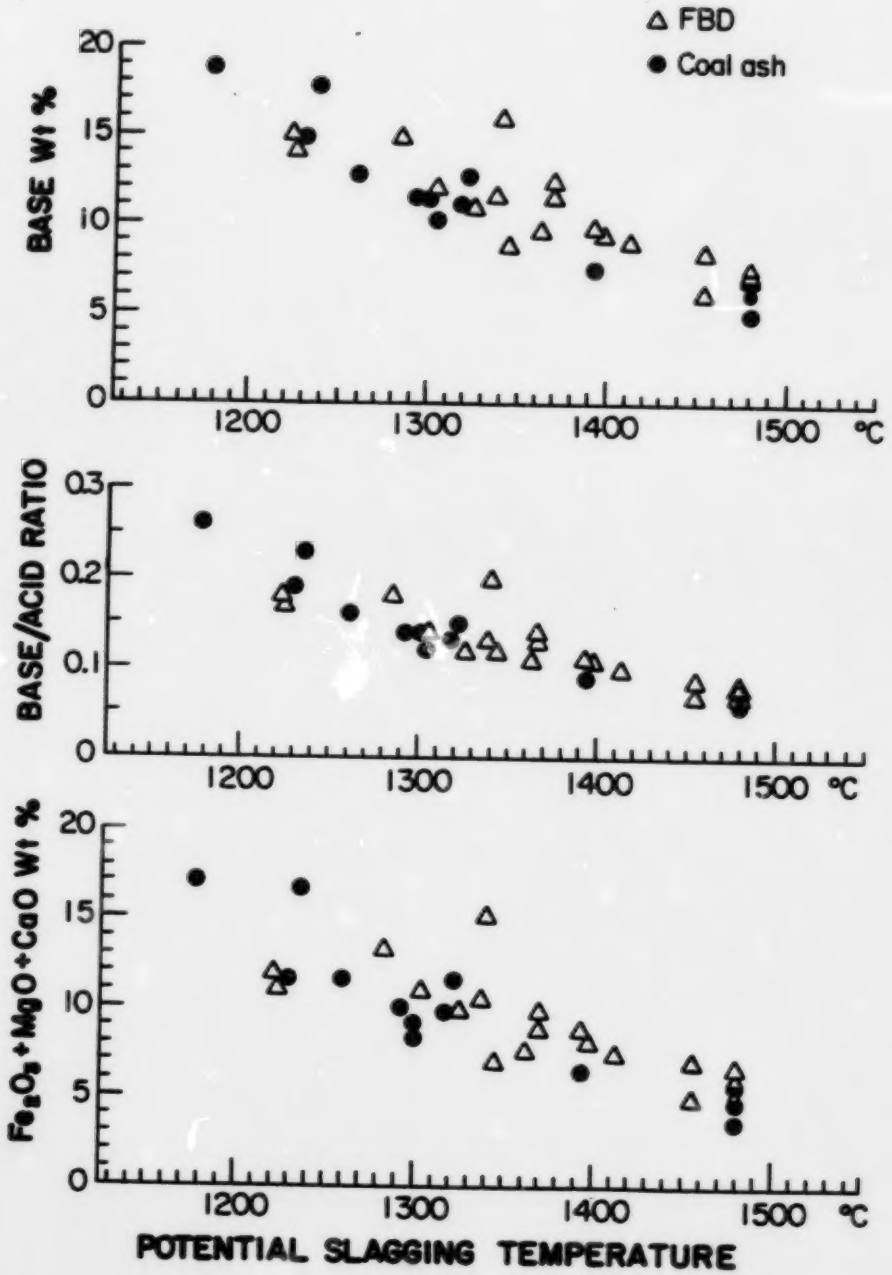

Fig. 9 – Correlations between potential slagging temperature and total base content, base/acid ratio, and total (CaO, MgO, Fe_2O_3).

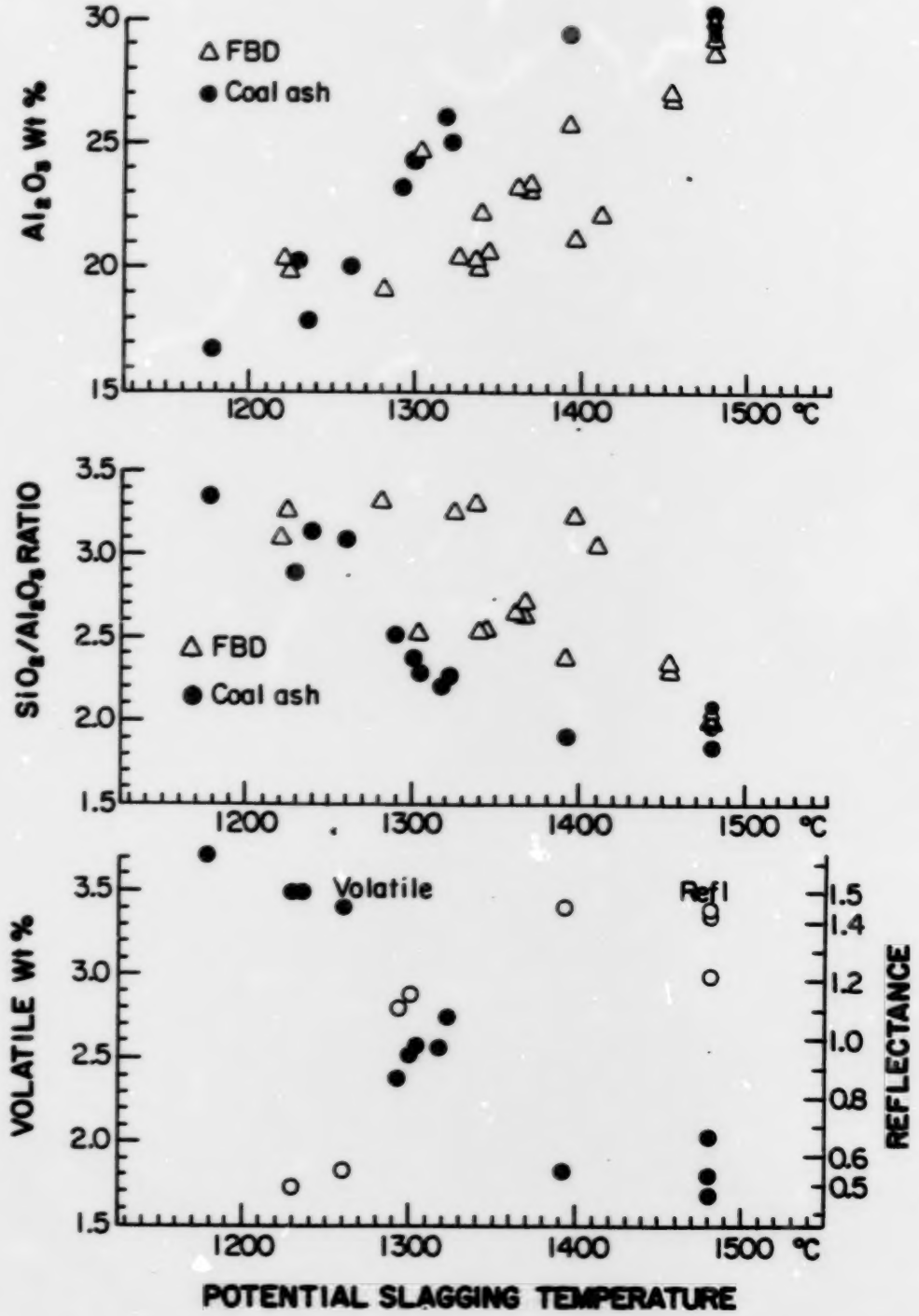

Fig. 10 - Correlations between potential slagging temperature and Al_2O_3 content, SiO_2/Al_2O_3 ratio of ash and FBD, volatile content and mean reflectance value of coal.

Table 1 - Furnace bottom deposits A317-82 and A390-82

Source	A blend of two washed high volatile subbituminous coals, containing 17.0 wt % ash, 34.8% volatile matter and 48.2% fixed carbon after beneficiation was used.			
Combustion condition	A390-82 was produced from a combustion condition with a slightly lower fuel rate, finer coal grind and lower flue gas rate than A317-82.			
Ash fusibility, °C		Parent ash	Furnace bottom deposit A317-82	Furnace bottom deposit A390-82
	Reducing atmosphere			
	Initial deformation	1199	1199	1199
	Spherical soft.	1279	1254	1254
	Hemispherical deform.	1360	1299	1293
	Fluid temp.	1377	1343	1349
	Oxidizing atmosphere			
	Initial deformation	1266	1238	1232
	Spherical soft.	1299	1299	1293
	Hemispherical deform.	1349	1327	1316
	Fluid temp.	>1480	1354	1349
Composition, wt %	SiO_2	57.89	64.13	63.16
	Al_2O_3	20.11	19.70	20.35
	Fe_2O_3	3.79	4.60	4.56
	TiO_2	0.46	0.43	0.34
	P_2O_5	0.64	0.36	0.40
	CaO	6.42	5.43	6.18
	MgO	1.34	0.94	1.07
	SO_3	3.95	0.11	0.07
	Na_2O	2.34	1.94	2.08
	K_2O	0.95	1.13	1.07
	BaO	0.58	0.30	0.57
	SrO	0.18	0.12	0.13
	L.O.F.	0.72	0.71	0.83
	Total	99.37	99.90	100.81

Phase Characteristics

	A317-82	A390-82
Colour[1]	Olive black with trace greyish olive.	Olive black to greyish olive.
Texture	Glassy, porous, with a vesicular microstructure on cross-section.	Glassy, porous, and heavy, with a vesicular microstructure on cross-section.
Phase characteristics	Iron-calcium alumino-silicate glass with minor amounts of quartz, cristobalite and mullite uniformly distributed throughout the slag. Trace amounts of anorthite locally crystallized as needle-like crystals in the middle portion. Quartz appears to be a residual phase, mullite occurs as reaction rims on quartz grains.	Iron-calcium alumino-silicate glass with trace amounts subrounded inclusions of SiO_2 (with mullite rim) in the fire face portion; with increasing amount of anorthite crystallized from melt towards boiler wall. Trace amounts of FeO dendrite and Fe-Ti oxide also occur in the middle portion. In portion near boiler wall, the slag consists mainly of anorthite crystals in glass (minor) matrix; local concentration and contamination by Fe-Ti oxide (rim) and TiO_2 (core), and SiO_2-mullite spheroids occur adjacent to boiler wall.
Glass matrix	Containing major Si, Al; minor Ca, Fe, Na and traces of K, Mg, Mn and Ti.	Major Si, Al; minor Ca, Fe, Na, and trace K, Mg, Ti.
Crystalline phases[2]	Major quartz, minor cristobalite, mullite, trace anorthite, sekaninaite[3].	Quartz, anorthite, cristobalite, mullite, trace TiO_2 and Fe-Ti oxide.

1. ISCC-NBS colour name (Supplement to NBS Circular 553). 2. X-ray diffraction analysis. 3. $Fe_2Al_4Si_5O_{18}$.

Table 2 - Furnace bottom deposits A448-82 and A516-82

Source	A blend of three high volatile bituminous coals. After beneficiation, the coal contains 9.9 wt % ash, 34.3% volatile matter and 55.8% fixed carbon.			
Combustion condition	A516-82 was produced from boiler operating conditions with a finer fuel grind, a slightly lower fuel rate and a lower excess combustion air than those for A448-82.			
Ash fusibility, °C		Parent ash	Furnace bottom deposit A448-82	Furnace bottom deposit A516-82
	Reducing atmosphere			
	Initial deformation	1224	1313	1308
	Spherical soft.	1288	1366	1327
	Hemispherical deform.	1391	1404	1363
	Fluid temp.	1432	>1454	1442
	Oxidizing atmosphere			
	Initial deformation	1271	1321	1331
	Spherical soft.	1318	1406	1362
	Hemispherical deform.	1410	1433	1398
	Fluid temp.	1433	>1454	>1454
Composition, wt %	SiO_2	61.46	66.44	66.86
	Al_2O_3	19.97	20.33	20.54
	Fe_2O_3	4.31	4.84	4.53
	TiO_2	0.91	0.54	0.53
	P_2O_5	0.37	0.27	0.27
	CaO	6.02	4.59	4.32
	MgO	1.20	1.02	0.92
	SO_3	3.74	0.00	0.00
	Na_2O	0.34	0.21	0.30
	K_2O	0.86	0.92	0.92
	BaO	0.25	0.44	0.37
	SrO	0.10	0.07	0.06
	L.O.F.	0.72	0.97	0.83
	Total	100.25	100.64	100.45

Phase Characteristics

	A448-82	A516-82
Colour	Dark yellowish brown, olive grey to pale yellowish green.	Brownish grey to pale yellowish grey.
Texture	Glassy, porous, with a sponge-like microstructure on cross-section.	Glassy, porous, with a sponge-like microstructure on cross-section.
Phase characteristics	Alumino-silicate glass with minor amounts of SiO_2 and mullite inclusions in which mullite occurs as reaction rims on subangular to subrounded SiO_2 grains. Fractures commonly occur in these inclusions. More SiO_2, mullite and Fe oxide are present near the slag surface (towards fire side).	Alumino-silicate glass with minor amounts of SiO_2 (core) and mullite (rim) inclusions; fractures commonly occur associated with these inclusion; local concentrations of these inclusions also occur. Contains also very trace amounts of FeO spheroids.
Glass matrix	Containing major Si, Al; minor Fe, Ca, and trace K, Mg, Ti.	Major Si, Al; minor Fe, Ca, and trace K, Mg, Ti.
Crystalline phases	Mullite, cristobalite, quartz, trace Fe_2O_3.	Quartz, mullite, cristobalite.

Table 3 - Furnace bottom deposits A538-82 and A559-82

Source	A washed medium volatile bituminous coal, containing 9.3 wt % ash, 23.7% volatile matter and 67.0% fixed carbon after beneficiation.			
Combustion condition	A559-82 was produced from combustion conditions with a slightly lower fuel rate, finer coal grind, lower flue gas rate, but higher fuel moisture than those for A538-82.			
Ash fusibility, °C		Parent ash	Furnace bottom deposit A538-82	Furnace bottom deposit A559-82
	Reducing atmosphere			
	Initial deformation	1246	1403	1383
	Spherical soft.	1396	1453	1428
	Hemispherical deform.	1476	>1454	>1454
	Fluid temp.	>1482	>1454	>1454
	Oxidizing atmosphere			
	Initial deformation	1313	1427	1413
	Spherical soft.	1427	>1454	>1454
	Hemispherical deform.	1462	>1454	>1454
	Fluid temp.	1472	>1454	>1454
Composition, wt %	SiO_2	57.89	67.57	67.97
	Al_2O_3	23.10	22.12	21.13
	Fe_2O_3	4.35	3.93	4.64
	TiO_2	1.15	0.70	0.67
	P_2O_5	0.72	0.34	0.27
	CaO	4.44	2.58	2.46
	MgO	1.16	0.90	0.91
	SO_3	3.45	0.08	0.09
	Na_2O	0.42	1.26	1.12
	K_2O	1.10	0.33	0.34
	BaO	0.89	-	-
	SrO	0.18	-	-
	L.O.F.	0.48	-	-
	Total	99.33	99.81	99.60

Phase Characteristics

	A538-82	A559-82
Colour	Dark olive brown to pale yellowish green.	Olive grey to pale yellowish green.
Texture	Glassy, very porous, with sponge-like microstructure on cross-section.	Glassy and very porous, with sponge-like microstructure on cross-section.
Phase characteristics	Alumino-silicate glass with trace amounts of SiO_2 and mullite inclusions randomly dispersed in the glass matrix. Mullite occurs as reaction rims on subrounded SiO_2 grains. Fractures occur associated with these inclusions.	Alumino-silicate glass with trace amounts of subrounded inclusions of SiO_2 and mullite (reaction rims), and very trace amount of (Si,Zr) oxide randomly distributed in the glass.
Glass matrix	Containing major Si, Al; minor Ca, Fe, Na and trace Mg, Ti and K.	Major Si, Al; minor Fe, Ca, Na, trace K, Ti, Mg.
Crystalline phases	Mullite, quartz, cristobalite, minor to trace amount anorthite.	Mullite, quartz, cristobalite, minor anorthite, very trace (Si,Zr) oxide.

Table 4 - Furnace bottom deposits A601-82, A622-82 and A581-82

Source	A low volatile bituminous coal (LC) containing 19.0 wt % ash, 20.2% volatile matter and 60.8% fixed carbon, was blended with a more reactive coal (R) containing 10.9% ash, 34.8% volatile matter and 54.4% fixed carbon in weight ratios of 60LC/40R and 80LC/20R.
Combustion condition	A581-82 was produced from reference coal R, A601-82 was produced from blend 60LC/40R, and A622-82 from blend 80LC/20R. The combustion conditions are similar except that A601-82 was produced from a slightly higher fuel rate than the others.

Ash fusibility, °C	Parent ash				Furnace bottom deposit		
Reducing atmosphere	LC	R	60LC/40R*	80LC/20R*	A581-82	A601-82	A622-82
Initial deformation	>1480	1191	-	-	1273	>1454	>1454
Spherical soft.	>1480	1254	-	-	1295	>1454	>1454
Hemispherical deform.	>1480	1302	-	-	1312	>1454	>1454
Fluid temp.	>1480	1418	-	-	>1454	>1454	>1454
Oxidizing atmosphere							
Initial deformation	>1480	1260	-	-	1295	>1454	>1454
Spherical soft.	>1480	1296	-	-	1312	>1454	>1454
Hemispherical deform.	>1480	1416	-	-	1323	>1454	>1454
Fluid temp.	>1480	1438	-	-	>1454	>1454	>1454
Composition, wt %							
SiO_2	61.14	55.55	58.9	60.0	63.20	61.76	63.70
Al_2O_3	25.59	17.70	24.8	27.2	19.09	26.97	26.95
Fe_2O_3	2.79	6.41	4.2	3.5	5.82	3.92	2.99
TiO_2	1.46	0.66	1.1	1.3	0.70	1.17	0.92
P_2O_5	0.42	0.21	0.3	0.4	0.03	0.03	0.02
CaO	1.29	8.86	4.3	2.8	6.57	2.29	1.29
MgO	0.69	1.30	0.9	0.8	1.04	0.75	0.56
SO_3	0.37	3.55	1.6	1.0	0.05	0.12	0.16
Na_2O	0.23	0.38	0.3	0.3	0.79	0.71	0.43
K_2O	1.39	0.75	1.1	1.3	0.55	0.84	0.90
BaO	0.17	0.36	0.3	0.2	-	-	-
L.O.F.	1.45	2.16	1.7	1.6	-	-	-
Total	96.99	97.89	99.5	100.4	97.84	98.56	97.92

Phase Characteristics

	A601-82 (60LC/40R)	A622-82 (80LC/20R)	A581-82 (R)
Colour	Moderate brown to greyish brown (rust color).	Yellowish white to yellowish grey (bone color).	Black to olive black.
Texture	Sintered-like, friable, non-glassy, with a very fine sponge-like texture on cross-section.	Very friable, powdery and light weight, with a very sponge-like texture on cross-section.	Glassy and porous, with a vesicular texture on cross-section.
Phase characteristics	Alumino-silicate glass with minor amounts of mullite, SiO_2, and trace amounts of Fe oxide, hercynite and (Zr,Si) oxide randomly dispersed in the glass matrix. Mullite usually occurs as fine-grained aggregates and as rim on SiO_2 grains.	Alumino-silicate glass, with major amounts of cristobalite, quartz and mullite, and trace amounts of Fe oxide randomly dispersed in the glass matrix.	Calcium-iron alumino-silicate glass with minor amounts of sub-rounded SiO_2 and mullite and trace amounts of anorthite, FeO and hercynite randomly but uniformly dispersed in the glass matrix.
Glass matrix	Containing major Si, Al; minor Ca, Fe, K and trace Ti, Mg, Na.	Major Si, Al; minor Fe, Ca, K, trace Ti, Mg.	Major Si, Al; minor Ca, Fe, trace Ti, K, Mg.
Crystalline phases	Major mullite, minor quartz, cristobalite, trace Fe_2O_3(?) hercynite.	Major cristobalite, quartz, mullite, minor Fe_2O_3, trace clay mineral(?)	Major quartz, cristobalite, minor mullite, anorthite, trace Fe[illegible], hercynite.

*Chemical composition calculated on the basis of blend ratio.

Table 5 - Data for coal ashes and furnace bottom deposits

Sample	Coal			Coal ashes and furnace bottom deposit						
Ash/FBD[1]	Rank	Volatile[2]	Reflect.	FBT[3]	$(CaO+MgO)/Fe_2O_3$	Base/Acid[4]	Base[2]	$Fe_2O_3+CaO+MgO$[2]	Al_2O_3[2]	SiO_2/Al_2O_3
Coal ash	High volatile	34.8	0.49	1229	2.05	0.19	14.84	11.55	20.11	2.88
A317-82	subbituminous			1225	1.38	0.17	14.04	10.97	19.70	3.26
A390-82	(blended coal).			1222	1.59	0.18	14.96	11.81	20.35	3.10
Coal ash	High volatile	34.3	0.54	1261	1.68	0.16	12.73	11.53	19.97	3.08
A448-82	bituminous			1337	1.16	0.13	11.58	10.45	20.33	3.27
A516-82	(blended coal).			1326	1.16	0.12	10.99	9.77	20.54	3.26
Coal ash	Medium volatile	23.7	1.1	1292	1.29	0.14	11.47	9.95	23.10	2.51
A538-82	bituminous.			1413	0.89	0.10	9.00	7.41	22.12	3.05
A559-82				1397	0.73	0.11	9.47	8.01	21.13	3.22
Coal ash LC	Low volatile bitm.	20.2	1.2i	1480	0.71	0.07	6.39	4.77	29.59	2.07
Coal ash E	(reference)	34.8	-	1236	1.59	0.23	17.70	16.57	17.70	3.14
A581-82	Coal E			1284	1.31	0.17	14.77	13.43	19.09	3.31
A601-82	Blend 60LC/40E			1454	0.78	0.09	8.51	6.96	26.97	2.29
A622-82	Blend 80LC/20E			1454	0.62	0.07	6.17	4.84	26.95	2.36
Coal ash	Medium volatile	25.2	1.15	1300	2.04	0.14	11.36	9.14	24.36	2.37
A592-81	bituminous.			1362	1.60	0.11	9.64	7.46	23.29	2.65
A613-81				1344	1.30	0.12	8.84	6.96	20.58	2.54
Coal ash	Medium volatile	25.8	1.0	1304	0.44	0.12	10.22	8.24	24.96	2.29
A519-81	bituminous.			1368	0.49	0.14	12.39	9.78	23.45	2.63
A545-81				1368	0.48	0.13	11.50	8.70	23.14	2.71
Coal ash A	Low volatile	16.8	1.44	1480	1.38	0.06	5.11	3.67	29.60	1.96
Coal ash B	bituminous.	18.2	1.45	1393	1.14	0.09	7.61	6.43	29.50	1.92
Coal ash C		18.0	1.42	1480	1.83	0.07	6.41	5.46	30.23	1.83
Coal ash D	(reference)	37.1	-	1177	2.32	0.26	18.70	17.02	16.72	3.34
Coal ash	Blend 60B/40D	25.6	-	1317	1.45	0.13	11.09	9.73	26.06	2.21
Coal ash	Blend 40B/60D	27.5	-	1322	1.28	0.15	12.83	11.49	25.02	2.28
A464-81	Coal B	-	-	1480	1.22	0.08	7.63	6.27	28.73	2.05
A484-81	Coal B	-	-	1480	1.36	0.07	6.57	5.45	29.42	1.98
A571-81	Coal C	-	-	1480	1.54	0.08	7.11	5.99	29.98	1.98
FBD	Blend 60B/40D	-	-	1393	1.10	0.11	9.91	8.73	25.82	2.37
FBD	Blend 40B/60D	-	-	1304	1.08	0.14	12.02	10.83	24.79	2.51
FBD-D	(reference)	-	-	1340	1.67	0.20	15.89	15.00	22.25	2.53

1. Furnace bottom deposit (FBD) is designated by sample number.
2. In weight per cent.
3. Potential slagging temperature, in C°.
4. Base = $Fe_2O_3 + CaO + MgO + K_2O + Na_2O$, Acid = $SiO_2 + Al_2O_3 + TiO_2$, in wt %.